Formation of Activation Products in Radiation Therapy

Syed M. Qaim

*Forschungszentrum Jülich GmbH*

Jülich

Germany
Formation of Activation Products in Radiation Therapy

Syed M. Qaim

INM-5: Nuklearchemie
Forschungszentrum Jülich GmbH
D-52425 Jülich, Germany

Lecture delivered during the Workshop on Nuclear Data for Science and Technology: Medical Applications, Abdus Salam ICTP, Trieste, Italy, 30 September to 4 October 2013
Topics

- General considerations
- Activation products in photon therapy
- Activation products in fast neutron therapy
- Activation products in proton therapy
  - short-lived $\beta^+$ emitters formed in human tissue
  - activation of beam collimators
- Conclusions
## Materials of Interest in Radiation Therapy

Composition of main materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Elements (mass %)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H</td>
</tr>
<tr>
<td>Muscle tissue</td>
<td>10.06</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>4.72</td>
</tr>
</tbody>
</table>
| Collimators    | Ti, Cu, Zn, brass, W, Pb, etc.     |        |        |       |       |       |       |       |       | (varying compositions)
Activation Cross Section Needs

- Formation of short-lived $\beta^+$ emitters in human tissue
- Estimation of long-lived activation products in biologically relevant elements
  - formation of tritium
  - formation of $^7$Be
  - formation of $^{22,24}$Na and other medium mass products
- Estimation of collimator activation in therapy facilities
### Some Possible Activation Products

<table>
<thead>
<tr>
<th>Material</th>
<th>Activation product</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short-lived $\beta^+$ emitters</td>
</tr>
<tr>
<td>Tissue</td>
<td>$^{10}$C (19.3 s); $^{11}$C (20.3 min); $^{13}$N (10 min); $^{14}$O (70.6 s); $^{15}$O (2 min); $^{17}$F (64.8 s); $^{18}$F (110 min)</td>
</tr>
<tr>
<td>Bone</td>
<td>above mentioned nuclides; additionally $^{30}$S (1.18 s); $^{31}$S (2.58 s); $^{30}$P (2.5 min); $^{38}$K (7.6 min)</td>
</tr>
<tr>
<td>Trace elements</td>
<td></td>
</tr>
<tr>
<td>Collimator materials</td>
<td></td>
</tr>
</tbody>
</table>
Types of Radiation Therapy

● **Photon therapy**
  - using $\gamma$-rays emitted from radionuclides ($^{60}$Co, $^{137}$Cs, $^{192}$Ir, etc.)
  - using high energy photons from accelerators

● **Fast neutron therapy**
  - using $p$(Be) or $d$(Be) neutrons (at $E_p$ or $E_d$ above 50 MeV)

● **Charged particle therapy**
  - proton therapy with $E_p = 70 – 250$ MeV
  - heavy-ion beam therapy (rather specialized)
Photon Therapy

- Most common form of radiotherapy
- Due to very high thresholds of photonuclear reactions, formation of activation products in tissue is negligible.

Example: $^{12}\text{C}(\gamma, n)^{11}\text{C} \ (T_{1/2} = 20 \text{ min})$


Only very high-energy bremsstrahlung could produce some positron emitter.
Photon Therapy (cont’d)

The activation of collimator material is also expected to be low, because the thresholds of photonuclear reactions are rather high.

Example: $^{66}\text{Zn}(\gamma,n)^{65}\text{Zn}$ ($T_{1/2} = 244.3$ d)

Fast Neutron Therapy

- Many nuclear reactions are possible, e.g. \((n,\gamma)\), \((n,xn)\), \((n,xp)\), \((n,x\alpha)\), \((n,t)\), etc.
- Kinetic energy released in matter (KERMA factor) makes LET-value of neutrons high.
- Several activation products are formed.
- Activation of medium and heavy mass elements is much stronger than that of light elements.
- Activation data needs in fast neutron therapy are extensive, but this therapy mode is being abandoned.
Fast Neutron Activation

Examples of Excitation Functions

$^{16}\text{O}(n,p)^{16}\text{N}$
$(T_{1/2} = 7 \text{ s})$

$^{31}\text{P}(n,\alpha)^{28}\text{Al}$
$(T_{1/2} = 2.2 \text{ min})$

$^{23}\text{Na}(n,2n)^{22}\text{Na}$
$(T_{1/2} = 2.6 \text{ a})$

Tritium Formation in Neutron Interactions


- 53 MeV d(Be) neutrons on elements
- Tritium formation cross section is fairly high in light mass region.
- In heavier mass region the formation of activation product via (n,p2n) process is much stronger than via (n,t) reaction
Charged-Particle Therapy

- Charged particles used: p, α, $^12$C, $^{14}$N, etc.

**Depth-dose relationship**

- Charged-particle dose increases with the penetration depth, reaching a maximum in the Bragg peak area.
- Major advantage of charged-particle therapy is the capability to treat deep-lying tumours, close to critical structures (due to high-selectivity of the Bragg peak).
- Heavy-ion therapy is specialized; proton therapy is more common and cheaper.
Formation of Short-Lived $\beta^+$ Emitters in Human Tissue in Proton Therapy

Short-lived $\beta^+$ emitters generated:

$^{11}$C ($T_{1/2} = 20$ min), $^{13}$N ($T_{1/2} = 10$ min), $^{14}$O ($T_{1/2} = 1.15$ min),
$^{15}$O ($T_{1/2} = 2$ min), $^{18}$F ($T_{1/2} = 110$ min), etc.

Examples of nuclear reactions

- $^{12}$C(p,$pn$)$^{11}$C
- $^{14}$N(p,$\alpha$)$^{11}$C
- $^{16}$O(p,$\alpha$)$^{13}$N
- $^{15}$N(p,$n$)$^{15}$O
- $^{18}$O(p,$n$)$^{18}$F
- $^{16}$O(p,$pn$)$^{15}$O

**Significance of data**

a) Estimation of extra dose due to activation products

b) PET investigation of the patient after proton therapy (utilizing the $^{11}$C formed in the tissue); localises dose distribution in the treated area
Formation of Short-Lived $\beta^+$ Emitters

(Protons on human tissue)


$^{11}\text{C} \quad ^{13}\text{N}$

- Improved data base $> 50$ MeV
Estimated Activity in Bragg Peak Region as a Result of Proton Therapy

**Assumption:** 200 MeV proton, 2 nA, 2 min irradiation

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Activity (MBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Muscle tissue</td>
</tr>
<tr>
<td>$^{11}$C</td>
<td>6.5</td>
</tr>
<tr>
<td>$^{13}$N</td>
<td>3.9</td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>121</td>
</tr>
</tbody>
</table>

Total activity of $\beta^+$ emitters:
- 131 MBq (in muscle tissue)
- 22 MBq (in cortial bone)

Other activities:
- $^7$Be (in muscle tissue): 40 kBq
- $^{22,24}$Na (in bone): < 250 Bq
Systematics of Excitation Functions of (p,\(^7\)Be) Reactions

- Probability of \(^7\)Be emission decreases with increasing mass of the target nucleus

Scholten et al., RCA 65, 81 (1994).
Activation of Beam Collimators

- Proton therapy demands high quality beams
- Tailoring of energy and homogenisation of intensity are achieved through collimators
- Activation of collimators is of some concern
- Commonly used collimators include titanium, brass, tungsten, etc.
Results for an Element as Collimator (Easily detectable products)

Example: $^{nat}$Cu$(p,x)^{55,56,58}$Co processes

- Model calculations reproduce experimental data well up to $E_p \leq 120$ MeV

Fassbender et al., ARI 48, 1221 (1997).
Results for an Element as Collimator
(Products difficult to detect)

Example: $^{\text{nat}}\text{Ti}(p,x)^{45}\text{Ca}$ ($T_{1/2} = 163$ d)

- Radiochemical measurement
- Good agreement between experiment and theory over the whole energy range

Qaim et al., RCA 98, 447 (2010).
Products difficult to detect (cont’d)

Example: $^{nat}\text{Pb}(p,x)^{204}\text{Tl}$ ($T_{1/2} = 3.78$ a)

Qaim et al., RCA 98, 447 (2010).

- Radiochemical measurement
- Good agreement between experiment and model calculations up to 60 MeV; at higher energies TALYS results are closer to experiment
Results for an Alloy as Collimator

Example: Formation of $^{52,54}$Mn from brass

- Model calculation reproduces experimental data with partial success up to proton energies of about 120 MeV.

Fassbender et al., ARI 48, 1221 (1997).
Activation of Brass Collimator

Assumptions

- 200 MeV, 400 nA p beam
- periodical running sequence
- two patients treated on one day of the week

• Estimated $^{54}\text{Mn}$ activity/year: 37.5 MBq
• Dose rate (at 1m): 4.8 µSv/h

Proper shielding of therapy facilities is mandatory
Conclusions

- Activation products formed in human tissue during photon and neutron therapy can be regarded as negligible.

- Formation of short-lived $\beta^+$ emitters is of some significance in proton therapy. The total activity (~120 MBq) is sufficient for dose localisation via PET studies; the extra dose from $\beta^+$ emitters is, however, negligible (<1%).

- Activation of beam collimators (both at neutron and proton therapy facilities) is of some concern regarding the therapy personnel.